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Recent advances on biopolymeric plant-based edible coatings and films: Antimicrobial strategies for enhanced food safety

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ABSTRACT

Edible film and plant-based materials have emerged as promising alternatives for traditional packaging materials and provide eco-friendly and sustainable options. Edible films are thin layers (usually <0.3 mm) that have been utilized for generations to protect food products and prevent ingredient deterioration. The importance of plant-based materials made from polysaccharides, proteins, and lipids is highlighted in this review, which also demonstrates their biodegradability and renewability. Also, explored edible films mechanical strength, barrier properties, optical properties, thermal stability, and shelf-life extension to prove their appropriateness for food packaging. Additional capabilities and advantages are provided via functionalization techniques, including active and intelligent packaging, addition of bioactive substances, and antibacterial properties. Various fabrication technologies (extrusion, solvent casting, dipping, spraying, etc.) have been considered for the formation of edible films and coatings. Furthermore, the significance of sustainability, scalability, regulation, and performance optimization is emphasized in the identification of challenges and future directions. By lowering the dependency on fossil fuels to minimize plastic waste and foster a circular economy, the potential benefits of plant-based materials and edible films can be emphasized. The various types of plant-based materials such as polysaccharides, proteins and lipids were profoundly used for the formulations of the edible films. Antimicrobial compounds are used in edible film and coatings to prevent the growth of germs and improve food safety and shelf-life. During storage, significant amounts of these substances remain on the food surface and are released through evaporation or diffusion depending on whether they are volatile or not. In conclusion, plant-based materials and edible films have the potential to revolutionise the packaging industry by offering sustainable alternatives to conventional materials. Adopting these innovations will promote the circular economy, minimize plastic waste, and make the world more resilient and sustainable.

1. Introduction

Food packaging provides information, confinement, and marketing. Their main purpose is to isolate food from the environment, reduce spoilage, and preserve useful compounds, extending its shelf-life. Petroleum-based polymers and plastics have grown in food packaging due to their low cost and desired properties. Unfortunately, these polymers are not biodegradable or renewable. Over 32 million tons of plastic waste are produced in the US annually. Less than 3 % of waste plastic is recycled due to technological and economic barriers [1].

Abbreviations: AM, Antimicrobial; AO, Antioxidant; WBC, Water binding capacity; OBC, Oil binding capacity; EOs, Essential oils; SPI, Soy protein isolate; BC, Bacterial cellulose; CNFs, Cellulose nanofibers; NCC, Nanocrystalline cellulose; SE, Shelf-life extension; YPI, Yellow pea isolate; YPC, Yellow pea concentration; TiO_2-NPs, Titanium oxide nanoparticles; ZnO-NPs, Zinc oxide nanoparticles; LNPs, Lignin nanoparticles; WVP, Water vapor permeability; DOLE, Dried olive leaf extract; ROS, Reactive oxygen species; LCA, Life cycle assessment; TVN, Total volatile nitrogen.

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Consumers want natural, high-quality, eco-friendly, and safe food packaging, which is also handy, as they become more concerned about environmental effects. The food industry faces a tremendous problem in producing sustainable packaging, while limiting the environmental impact. To address these needs, the food industry has focused on producing biodegradable, edible, and sustainable materials that can enhance food safety and quality [2]. Proteins (soy protein, pea protein, and sunflower), polysaccharides (starch, pectin, cellulose, and *aloe vera*), lipids (oils and free fatty acids), and waxes are commonly employed in the food industry to produce edible films and coatings used in the packaging of various food items. Films created from edible materials improve the organoleptic, nutritional, and microbiological qualities of food items, while also being environmentally beneficial. Furthermore, as food items are prone to gradual alterations during storage and distribution, these films act as a barrier for oxygen, water vapor, and moisture, resulting in an extended shelf-life [3]. Bioactive compounds can enhance the antibacterial and antioxidant characteristics of edible films and improve the shelf-life of food products. Other features that make edible films and coatings more suitable include antioxidants, antimicrobials, shelf-life extension (SE), nutritional content preservation, and barrier properties. Several technologies have been applied to the fabrication of edible films and coatings. The methods considered for the fabrication of are extrusion and solvent casting. An edible coating is a thin layer of edible substance that forms as a protective covering for meals and can be consumed alongside them. Edible coatings employ technologies such as dipping, spraying, and panning. These technologies vary depending on the type of food the films/coatings are applied to and in accordance with industry requirements as well as accessibility. Degradability is a major benefit of edible films and coatings. The food industry applies edible films and coatings to different foods based on their chemical makeup, molecular structure, and storage type. These films and coatings are utilized for the packaging of fruits, vegetables, meat, poultry, fish, dairy products, bakeries, and confectioneries. This plant based formulated edible films show varying properties which include antimicrobial effect, antioxidant mechanism, moisture barrier and several others. Another primary benefit of utilizing edible coatings is the possibility of incorporating various active substances within the matrix of the coating, contributing to improving its organoleptic and nutritional properties, which emphasizes the target nutrient supply. These properties of films and coatings thus show profoundness in extending the shelf-life of the food items. The edible films utilized upon the food items involve a variable range of packaging system which are regarded as smart packaging systems that act as intelligent as well as active packaging. Active packaging includes components that release or take in substances from food or the environment, extending shelf-life while maintaining safety, quality, and consumer acceptability. While, smart packaging technology includes systems that precisely monitor changes occurring within the food product. Food goods require specialized packaging to meet their specific physical, chemical, and physicochemical requirements. Edible films and coatings show promise as taste and active ingredient delivery technologies that enhance food quality and usefulness. Some of the limitations of these plant-based films are mechanical weakness, poor water resistance, scalability issues, or cost-effectiveness [4]. Many plant-based materials biodegrade, but their speed and compatibility with waste management systems must be considered. Regulators, corporations, and researchers must collaborate to promote innovation and knowledge exchange. Working together will make it easier to create uniform plant-based material and edible film safety and food packaging policies. This review emphasizes the relevance of plant-based materials composed of polysaccharides, proteins, and lipids, as well as their biodegradability and renewability. To demonstrate edible film's suitability for food packaging, we further investigated its mechanical strength, barrier qualities, optical properties, thermal stability, and shelf-life extension.

2. Sources of plants-based edible films and coatings

Edible coatings and films were categorized according to their structural compositions. The major molecular categories are polysaccharides, proteins, lipids, and resins, which can also include combinations of these (Fig. 1). Additives can improve physical and functional characteristics. Edible films are built of renewable, edible, and environmentally acceptable materials, which could improve the value of food and agriculture byproducts. Lipid-based films are water-resistant. High mechanical strength makes proteins and lipid-based films easier to handle. Thus, blends containing these chemicals or lipids can be used to create composite edible films that meet food packaging standards [5].

2.1. Polysaccharides

2.1.1. Starch and its derivatives based edible films

Starch is a biopolymer found in the endosperm of plants, and in the roots and legumes of immature fruits and tubers [6]. Starch granules absorb water around their free hydroxyl groups and swell; this swelling continues until a threshold concentration is reached. [7]. Starch-based edible films and coatings can replace plastic packaging owing to their special qualities, which include low cost, thermoplastic nature, low permeability to oxygen, ease of access, and excellent resolution [8]. The type of starch and the ratio of amylose and amylopectin influence the color, thickness, moisture, and mechanical properties of the films and Coatings. Amylose, which has a helical structure, causes film development. Starch films with a higher concentration of amylose have superior mechanical strength, gas barrier properties, and flexibility [9]. Starch-based films provide a barrier against oxygen and carbon dioxide. However, because of its high hydrophilicity, it has poor water-barrier properties [10]. A previous study found that when starch-based film is modified by torch ginger inflorescence essential oil and is applied to chicken flesh, a reduction in coliform and lipid oxidation is observed [11]. Another study demonstrated that the application of grape juice-induced maize starch to chicken breast fillets reduced the overall aerobic mesophilic, psychrophilic, and Enterobacteriaceae counts [12]. Researchers have also found that when corn starch-chitosan-based Coatings material modified with pomegranate peel extract and *Thymus kotschyanus* essential oil was applied to fresh beef slices, an overall reduction in bacteria and lipid oxidation was observed even after 21 days of storage [13]. Ground beef treated with ginger starch and coconut shell liquid smoke-induced film showed a decrease in *E. coli* population and lipid oxidation over the course of 12 days at 4 °C [14].

2.1.2. Pectin based edible films and coatings

Plant cell walls are rich in pectin and some fruits (citrus fruits and apples) have high pectin concentrations when they are fully mature. Owing to its unique qualities, such as odorlessness, non-toxicity, biodegradability, affordability, renewability, and low gas permeability, it is a good biopolymer for edible films or coatings [15]. Excellent mechanical properties, such as a barrier to oil, oxygen, and fragrance, are observed in pectin-based edible film. However, they exhibit poor durability against moisture, low expansions, and are brittle; the addition of plasticizers increases their flexibility [16]. The stabilization and physicochemical properties of pectin-based edible films or coatings can be improved by combining pectin with biopolymers. Meat and meat products have long been preserved using edible film or coatings made of pectin-containing bioactive substances [17]. Pectin films with polyvalent cations such as calcium have decent mechanical characteristics. Pectin films and gels work well to preserve food with little moisture [18]. High-methoxy pectin edible film has several advantageous properties. Strong, flexible, edible, and biodegradable films are produced through the plasticization of pectin and starch with high amylase content. These films then undergo plasticization with glycerol to provide an excellent mechanical and oxygen-barrier qualities [19].

In a previous study, citrus pectin (which has a 53 % esterification

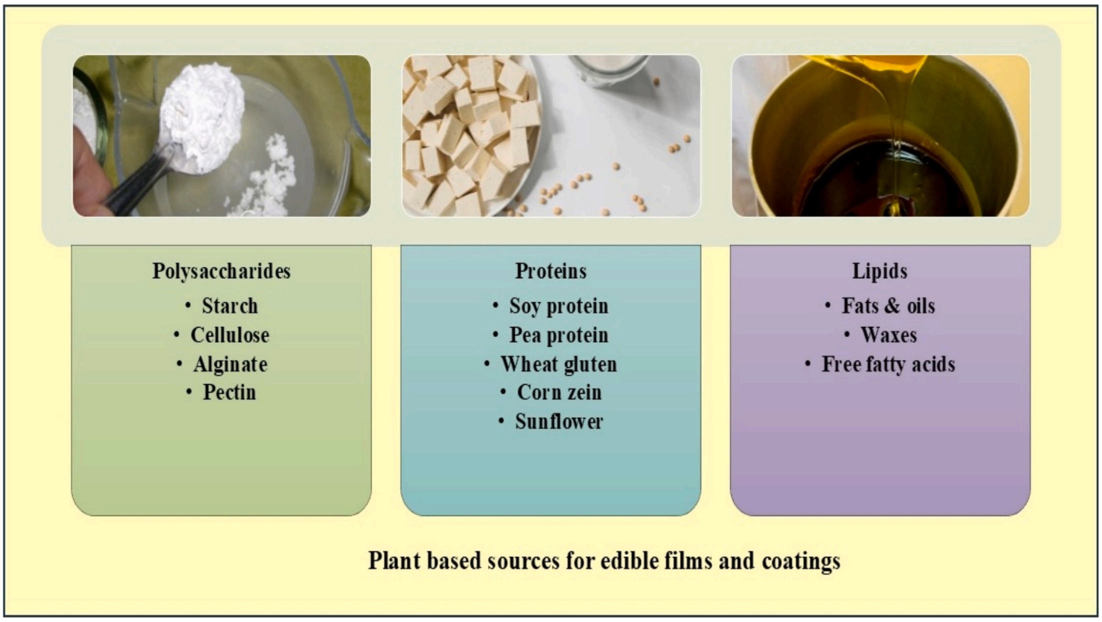

Fig. 1. Plant based sources.

degree) and fish skin gelatin integrated with hydroxytyrosol and 3,4 dihydroxyphenylglycol from olive oil by-product to beef meat improved the lipid stabilization of the coated samples by 68 % and 59 %, respectively [20]. Another study stated that when applied to chilled mutton, watermelon pectin and polyphenols reduced the amount of Total Volatile Nitrogen (TVN) and thiobarbituric acid (TBA) in coated samples that included 1.5 % of watermelon peel polyphenols. This also decreases the overall number of bacteria [21]. Another study reported that when pectin combined with oregano essential oil was applied to a large yellow croaker fillet, the number of total viable bacteria, Pseudomonas, and H_2S-producing bacteria significantly decreased. Decreases in TVN and TBA values as well [22]. When combined with pectin and cinnamic acid, sodium alginate and fresh beef loins help to limit the growth of microorganisms [23].

2.1.3. Cellulose-based edible films and coatings

Cellulose is the most abundant organic substance on earth. It is composed of D-glucose units connected by β-1,4 glycoside linkages. Its derivatives are commonly used to create edible films that are biodegradable, odorless, and tasteless [24]. Commonly used cellulose derivatives include methylcellulose, hydroxypropyl methylcellulose, and carboxymethyl cellulose [25]. Nanoparticles can be removed using top-down mechanical and chemical deconstruction techniques. Mechanical treatment produces cellulose nanofibers, whereas acid hydrolysis produces cellulose nanocrystals [26]. The application of nanocellulose using starches as a reinforcing element in food matrices enhances the thermomechanical characteristics, reduces water sensitivity, and maintains biodegradability. Mixing nanocellulose with polysaccharides (like starch) increases its mechanical characteristics [27]. Carboxymethyl cellulose (CMC) has been shown to minimize oil uptake in fried potatoes, especially when combined with blanching or calcium chloride pretreatment. Methylcellulose showed a superior moisture barrier because it is less hydrophilic. However, their most intriguing feature is their thermally treated foods, particularly fried products [28].

2.1.4. Alginate-based edible films and coatings

Alginate is a cost-effective, recyclable, biocompatible, homogeneous, clear, water-soluble, and non-toxic biomacromolecule that forms films or coatings [29]. Its fibrous chemical structure and gelling capabilities make it ideal for producing high-quality films and coatings [30]. Sodium alginate (SA) is a prominent polysaccharide with good colloidal characteristics and significant sensitivity to polyvalent metal cations, forming gels or insoluble polymers. Owing to its ability to create a semi-permeable barrier, it is commonly used as an edible coating to preserve apples, peaches, mushrooms, and broccoli [31]. A study on capsicum showed that coatings with 2 % alginate and 1 % pomegranate peel extract can effectively preserve and protect chlorophyll, ascorbic acid, firmness, and color while preventing fungal growth when stored at a temperature of 10 °C [32]. A study evaluated novel films enhanced with 0.75 g extract/g alginate green tea and grape seed extracts. Alginate films containing green tea extract showed greater inhibitory activity against murine norovirus and hepatitis A virus. They have stronger antioxidant activity and better water barrier characteristics than those of films formed using grape seed extracts [33].

2.1.5. Carrageenan-based edible films and coatings

Carrageenan is mostly derived from the genera *Chondrus*, *Eucheuma*, *Gigartina*, and *Iridaea*, which are hydrophilic linear sulphur galactans present in the cell walls of red sea algae (*Rhodophyceae*). Its structure mostly comprises galactose and ester sulphate groups, but also contains other polysaccharide residues such as glucose, xylose, uronic acids, methyl ethers, and pyruvate groups [34]. Owing to its linear chain of partly sulphated galactans and water solubility, carrageenan has many applications in film formation [35]. A previous study reported that films formed by combining κ-carrageenan with alginate showed improved mechanical, thermal, and optical characteristics [36]. Carrageenan films modified with nanoparticles, such as ZnO and CuO, exhibit increased elongation at break, thermal stability, and antibacterial activity against *E. coli* and L. *monocytogenes* [37].

2.1.6. Aloe vera based edible films and coatings

Aloe vera is rich in bioactive compounds, such as flavonoids, terpenoids, lectins, fatty acids, anthraquinones, mono- and polysaccharides, tannins, sterols, enzymes, salicylic acid, minerals, and vitamins [38]. *Aloe vera* gel films and coatings can extend the shelf-life of perishable foods. Blending *aloe vera* gel with standard biopolymers (proteins and polysaccharides) and lipids (emulsions) appears to be a potential technique for fine-tuning film/coating qualities, such as transparency, smoothness, stiffness, elasticity, water vapor permeability, and biofunction [39]. *Aloe vera* gel is typically used as an edible covering for whole or fresh-cut fruits and vegetables after harvest and before commercialization [40]. According to a previous study, adding rosehip oil to *aloe vera* gel Coatings for plums and prunes reduced respiration rates [41]. In a study, *aloe vera* gel was applied to fresh-cut papaya at concentrations ranging from 5 to 50 %, and it was found that coated fruits had a reduced TSS level (8.29 %) compared to the non-coated control (10.50 %). Moreover, they found that 25 % *Aloe vera* gel was the optimum concentration for maintaining titratable acidity [42].

2.2. Proteins

Proteins are large molecules made up of about 100 amino acids, they can be altered using heat, acids, bases, or specific solvents [43]. This change makes them more suitable for forming films. Although protein-based films don't match the water resistance or strength of synthetic ones, they usually perform better than films made from polysaccharides when it comes to mechanical strength and barrier properties. Several factors play a role in how films behave, including the types of amino acids present, the charge on the protein, and their ability to interact with both water and fats [44]. To enhance the water vapor barrier and mechanical strength, proteins can be cross-linked using various methods. These include chemical agents like glutaraldehyde, formaldehyde, glyceraldehyde, and glyoxal; enzymatic approaches such as using transglutaminase; and physical treatments like heat or irradiation [45]. Among the proteins that can be utilized in edible films are collagen, lactic serum, caseinate, and seine. Because of their distinct structure, protein films have superior mechanical qualities than polysaccharides. In contrast to synthetic polymers, protein films have a higher water vapor permeability and a lower mechanical strength [46].

2.2.1. Wheat gluten

Soluble gliadins and insoluble glutenin, the two primary proteins that make up wheat gluten, can be distinguished from one another based on their solubility in 70 % ethanol [42]. Aqueous-alcohol solutions are frequently used in the formulation of wheat gluten films. In addition to adjusting the pH of the solution to alkaline or acidic, homogeneous film solutions are required to form gluten films through solvent casting [47]. Wheat gluten films are water-resistant, strong, homogeneous, and transparent. By limiting respiratory exchange, EF or coatings that let certain gases through could help fresh or barely processed fruits and vegetables last longer. Gluten films can become rubbery under excessive pressing [10]. Wheat gluten-based films have the best elasticity, oxygen barrier, hydrophobic surface, and thermal stability of any protein-based film. Wheat gluten-based films have high water vapor permeability (WVP) and low mechanical strength, which should be considered throughout development [48,49]. Researchers have used lignin nanoparticles (LNPs) in their investigation and found that at a 3 % LNP concentration, there was a significant increase in the tensile strength (141.8 %), Young's modulus (206.4 %), glass transition temperature (18.4 %), and water uptake (37.7 %) [50]. In a previous study, transglutaminase (20 units/g gluten) was added to a gluten-based film to apply the cross-linking process. The findings showed a minor decrease in elongation (7.6 %) and improvements in tensile strength and surface hydrophobicity (11.6 % and 28.5 %, respectively) [51]. Studies states that, adding "proanthocyanidin," a condensed sorghum tannin, to the gluten-based film at a dose of 10 mg/g increased film tensile strength by 128.5 % [49].

2.2.2. Corn zein

Corn zein is a protein extracted from corn, and is often made from corn gluten meal as a powder. Corn zein is insoluble in water and is transparent, tasteless, and odorless. It has numerous industrial and culinary applications, including fibers, chewing gum, adhesives, coatings, ceramics, inks, cosmetics, textiles, and biodegradable polymers. It is also being studied as a possible replacement for gluten. It accounts for up to 50 % of the total protein content of corn [42]. Corn zein coating prolongs the shelf-life of tomatoes by preventing color change, weight loss, and hardness loss [52]. Zein-based films also exhibit excellent thermal and tensile strengths, high transparency, and low oxygen permeability. Nevertheless, Zein film's primary drawbacks are its extremely brittle structure and lack of flexibility [53]. Studies have shown that corn-zein film prevents tomatoes from becoming stiff, slows down the ripening process, decreases weight loss, and delays color changes. The degree of color change is influenced by the Coatings thickness [54]. A study showed that the addition of 40 mg/g of gallic acid and 4 % of oleic acid to corn zein film resulted in an 18.9 % increase in the elasticity (elongation) of the film; however, there was no discernible change in the tensile strength and WVP [55]. Another research showed an increased in zein film's flexibility by 13 times by mixing it with chitosan in a 1:1 ratio [56].

2.2.3. Soy protein

Soy protein isolate (SPI) is essentially an impure protein composed of distinct globulin portions, which are present in non-uniform amounts and are categorized as 2S (8 %), 7S (35 %), 11S (52 %), and 15S (5 %) based on their sedimentation coefficients. A common option for raw materials in the production of protein-based materials is SPI, which has a high protein content (>90 %) among other proteins. In general, SPI-prepared films are smoother, more transparent, and more flexible than those prepared with other plant proteins. Hydrophilic and hydrophobic amino acids are included in the soy protein fraction control and affect the production of antibacterial compounds [57]. The practical applicability of SPI is limited by its hydrophilic nature, low mechanical strength, susceptibility to microbial attack, and inadequate moisture barrier capability. To improve the mechanical and bactericidal properties of SPI films, various naturally occurring phenolic acids, flavonoids, and extracts containing polyphenolic compounds have been added [58]. The antioxidant capacity of the SPI-curcumin complex was assessed using the DPPH radical scavenging assay. The fundamental mechanism of action of DPPH is to scavenge radicals and reduce absorbance when it comes into contact with a chemical that donates protons, such as an antioxidant [57]. The addition of polyphenol to SPI films and coatings can increase water resistance [59].

2.2.4. Pea protein

Pisum sativum, also known as yellow peas, is one of the main pulse crops. The proteins found in yellow peas consist of approximately 10–20 % albumins and 70–80 % globulins such as legumin (11S), vicilin (7S), and convicilin. Due to the high protein and bioactive component contents of pulses, this calls for expanding their use to encompass the creation of novel foods and value-added products. Therefore, using pulse proteins to create edible film offers a long-term way to increase the usage of pulses, while also producing bio-based packaging that is favorable to the environment [60]. The ideal film has good tensile strength, modulus, puncture resistance, appearance, and gas and water barrier properties [61]. Low molecular flexibility makes pea proteins unpredictable, making it difficult to produce a solid interfacial Coatings with oil. Pea proteins stabilize emulsions, lower water-oil interfacial tension, and produce a strong membrane at the oil-water interface. It has significant surface-active characteristics at the oil-water interface [62]. Yellow pea concentrates contain proteins, fibers, and phytochemicals that increase film surface energy breakdown while reducing protein concentration and active polar molecules [60]. Protein films' high surface hydrophilicity makes them ideal for wettability and visibility applications. However, protein acetylation and nanomaterial addition to composite films may increase hydrophobicity [63]. Proteins have the lowest solubility at their isoelectric pH because they carry zero net charges and their hydrophobic forces are higher than their electrostatic interactions with water molecules [64]. Pea protein has an optimum solubility of 80 % above pH 6 and <30 % between pH 4 and 6 [65]. One study found that pea protein concentrates and glycerol create more homogenous films with lower light transmission than whey proteins. Similar mechanical and physical properties were observed throughout the same period [66]. Additional research has revealed that combining sorbitol with pea proteins produces films with good transparency and tensile strength [67]. An acetylated cassava starch and pea protein isolate mixture improved film formability and mechanical properties in another investigation. Pea protein isolates improve surface hydrophobicity, tensile strength, protein aggregation, film stability, oxygen and water vapor barrier [68].

2.2.5. *Sunflower*

Proteins derived from sunflower (*Helianthus annuus* L.) meal after oil extraction appear to be excellent, affordable, and reliable substitutes for making packaging films that are sustainable and environmentally friendly. Sunflower seed proteins can function as durable and environmentally friendly biopolymer substrates [69]. The tensile strength and elongation at break were quite low, however adding 0.25–1 % parsley and rosemary oils resulted in enhanced antioxidant capabilities and elongation at break. In addition, the films possess a strong UV barrier [70]. Foodstuffs were shielded from photochemical reactions by sunflower seed composite films. Conversely, a drop in film transparency was shown by a decrease in absorption in the visible region. In terms of structure, the membranes lacked pores and fissures, and were compact and uniform. Additionally, the films demonstrated microbiological stability in six tests, indicating their safety for direct consumption with the selected products for packaging [71].

2.3. *Lipids*

Food lipids are typically the fats and oils found in foods. Chemical lipids are fatty acid polymers composed of long chains of nonpolar hydrocarbons with a small polar oxygen area. In this study, we examined the use of lipid components to create edible films with hydrophobicity, flexibility, and cohesion. Furthermore, lipid coatings provide a fantastic barrier against oxygen and moisture, allowing food to be kept fresh for longer periods of time. These edible lipid films and coatings also offer nutritional and functional qualities. Lipid films contain a hydrophobic barrier, which improves the barrier function and decreases water vapor permeability [72]. Lipids include tiny hydrophobic compounds such as fats, waxes, sterols, and fat-soluble vitamins. Owing to their non-polar properties, hydrophobic substances (lipids) are often used as barriers against water vapor transfer. Edible coatings and films have an extensive history of use to preserve fruits and vegetables, despite their current prominence. Waxes have been used for millennia to prevent moisture loss and preserve the freshness of vegetables and citrus fruits during storage [73]. Covering fruits and vegetables with wax can have adverse effects, including increased carbon dioxide concentrations that promote microbial growth, increased acetaldehyde and ethanol levels, and decreased overall solids owing to anaerobic respiration. Various fatty compounds can also add pleasant sheen to food products. Lipids are commonly employed in Edible coatings and films in meat, poultry, seafood, and other foods [74]. One study found that covering plums with rosehip oil delayed ripening and retained their freshness for longer periods of time. On day 14, the weight loss for control fruits was 15.6 %, whereas for treated fruits, it was 10.04 % [75]. Another study indicated that Coatings strawberries with lipid-based composite films and candelilla wax, along with biocontrol bacteria (*B. subtilis*), can effectively decrease bacterial deterioration [76].

3. Structure of biopolymers in the plant based edible films and coatings

The various forms of biopolymers that are usually derived from plant sources, along with their structure and origin are depicted schematically (Fig. 2). They are classified into two types: carbohydrates and proteins. Also, a variation of lipid compounds is utilized in formation of plant based edible films.

Polysaccharides are vast carbohydrate biopolymers found abundantly in higher photosynthetic plants. They are made up of hundreds of thousands of repeating monosaccharide units connected together by glycosidic linkages. They can also be derived from bacteria, fungus, and marine biomass. Their biocompatibility, biodegradability, and non-toxic features make them well-known and suited for a wide range of uses, particularly in the food packaging industries [77]. Starch is a remarkable carbohydrate composed of two α-glucose polymers: linear amylose

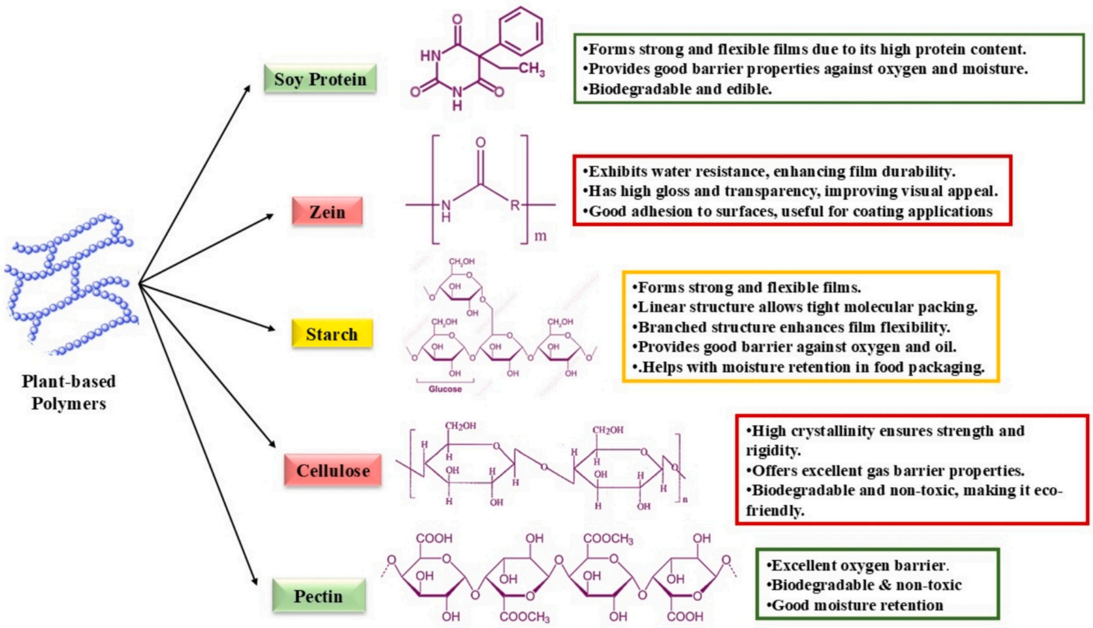

Fig. 2. The main varieties of plant-based biopolymers are soy protein, zein, starch, cellulose, pectin; their structure and the origin of extraction.

(poly-α-1,4-Dglucopyranoside) and highly branched amylopectin (poly-α-1,4-D-glucopyranoside and α-1,6-D-glucopyranoside). Amylose molecules generate helical structures through the interaction of bond angles within 200–20,000 glucose units. Amylopectin molecules are highly branched amorphous polymers made up of short-chain glucose units linked together with glucose units. Cellulose is one of the most prevalent biopolymers on Earth, with numerous industrial applications, particularly the food sector. The three primary forms of cellulose used in food packaging are micro fibrillated cellulose (MFC), nanocrystalline cellulose (NCC), cellulose nanofibers (CNF), and bacterial cellulose (BC) [78]. Gums are another type of plant-based polysaccharide. The chemical structure can be changed depending on the molecular weight, length of the main chain, moieties and branches, and interactions between hydroxyl groups, polar groups, and hydrogen bonds. Pectin, a crucial plant-based biopolymer that forms plant cell walls, is predominantly derived from citrus and apple wastes. This biodegradable polysaccharide is made up of methylated D-galacturonic acid (GalA) units and esters linked together by α-(1,4) glycosidic bonds. Pectin is categorized into two types based on its esterification degree: high methoxylated (HM) and low methoxylated (LM) [79]. Protein-based biofilms generated from plant resources such as soy, zein, gliadin, and lectins have been created for applications in food packaging due to their availability, sustainability, biodegradability, and excellent film-forming capabilities. Because of their hydrophilic nature, most protein-based films have a high-water vapor permeability and water-holding capacity. However, they have little oxygen permeability. Plant-derived proteins are preferred over animal-derived proteins because they require less extraction and can reduce immunogenicity and viral transmission [80].

4. Functional properties of plant-based edible films and coatings

4.1. Antioxidant

Antioxidants are used in food products to prevent lipid oxidation, which can cause off-flavours, odours, and hazardous aldehydes that are unsafe for human ingestion. Furthermore, product discoloration and loss of nutritional quality due to polyunsaturated fatty acid breakdown can occur, resulting in food spoiling and, subsequently, a reduction in product shelf-life [81]. Plant-based coatings used in food packaging can integrate antioxidant chemicals directly into the film or coating matrix, providing a controlled release mechanism to preserve food products. Vitamin E, C, polyphenols, carotenoids, tannins, and anthocyanins are common antioxidants found in plant-based food coatings. They can be obtained from soybeans, sunflower seeds, citrus fruits, green leafy vegetables, edible roots, tea leaves, and tree barks. Citrus fruits and berries contain ascorbic acid (Vitamin C), a potent antioxidant that protects against oxidative stress and regenerates other antioxidants such as α-tocopherol [82].

The protection of fresh strawberries and raspberries from foodborne pathogens, alginate coatings with green tea extracts were found to be highly effective [83]. Researchers have created biodegradable films based on cassava starch encapsulated with β-carotene for antioxidant properties [84]. A study discovered that blackberry powder was found to have antioxidant properties in arrowroot starch-based edible films. The antioxidant properties of blackberry and other plant extracts are related to their polyphenol and anthocyanin contents, which are retained when added to edible films [85]. Another study reported that the antioxidant activity of films incorporated with solubilized dried olive leaf extract (DOLE) was observed every five days until day 30. Despite some days of storage, the films with 10 and 15 % (v/v) DOLE showed lower antioxidant activity. It is evident that, compared to solutions comprising DOLE and film-forming solutions, the antioxidant activity values in solubilized films were lower. The outcomes of 20 % (v/v) DOLE-containing samples and 40 % (v/v) DOLE samples were comparable. One explanation might be that, when trapped in the edible film matrix, the phenolic chemicals found in DOLE exhibit reduced activity [86].

4.2. Antimicrobial

Antimicrobial compounds are used in edible films and coatings to prevent the growth of germs and improve food safety and shelf-life. During storage, significant amounts of these substances remain on the food surface and are released through evaporation or diffusion depending on whether they are volatile or not [81]. The use of synthetic antibacterial agents in packaging has raised concerns regarding their potential negative effects. The use of natural and safe antibacterial chemicals is highly recommended, particularly by consumers [87]. Antimicrobial agents in food packaging include organic acids, enzymes, bacteriocins, fungicides, polysaccharides, metal nanoparticles, liquid smoke, soy sauce, probiotic cells, plant extracts, and spices [88]. Fresh-cut pears were successfully treated with starch-based edible film-containing *Adiantum capillus-veneris* extract, preserving their freshness [89]. A study on edible film found that higher concentrations of smaller essential oil (EO) particles boosted antibacterial effectiveness [90]. EOs have been shown to have strong antibacterial effects at low pH, high temperature, and low oxygen concentrations. However, high protein and fat contents, as well as low moisture, can protect bacteria from essential oils [91]. Titanium oxide nanoparticles (TiO_2-NPs) and Zinc Oxide nanoparticles (ZnO-NPs) are examples of nanoparticles that can serve as antibacterial agents via photocatalytic processes. These components contribute to the generation of reactive oxygen species (ROS), which results in cytoplasm oxidation and bacterial cell death, as described in Fig. 3. Furthermore, layered systems like nanoclay can load compounds like antibacterial modifiers, providing multifunctional sites for additional reactivities. Nanolayers on emulsion structures increase mucosal adherence, allowing for targeted distribution of bioactives. They have been shown to have good synergistic effects on foodborne micro-organisms and other advantageous qualities like anti-ageing, antioxidant (AO), food preservation, and anti-cancer properties when incorporated in films [92].

Natural-based AM compounds show properties as eventual alternatives to antibiotics. These compounds are present in the roots, stems, leaves, flowers, fruits, and seeds of plants. In a study it was found that, cupcake made with wheat flour, the extracted EOs from orange peel demonstrated an inhibitory impact on a number of bacteria, including *Aspergillus niger* and *Penicillium* sp. [93]. Another study states that, the fungus population was lowered throughout a 60-day storage period at room temperature when 0.15 % of the extracted EO from coriander was added to a butter formulation. The primary ingredients of this EO were limonene, a-pinene, camphor, and cyclohexanol acetate, which may have contributed to the extract's AB properties [94]. A researcher, created a multilayer gellan gum-chitosan film that included a nano-emulsion of EO of thyme. In a liquid model system, this film dramatically decreased *E. coli* populations and possessed a sustained release feature [95]. TiO_2-NPs and ZnO-NPs are examples of nanoparticles that can serve as antibacterial agents via photocatalytic processes. These components contribute to the generation of ROS, which results in cytoplasm oxidation and bacterial cell death [96]. Metal and metal-oxide nanoparticles are also extensively explored for packaging applications. These materials have dual antibacterial activity against gram-positive and gram-negative bacteria. The primary targets for acceptable interactions/reactions are the multifunctionalities of metal and metal oxide NPs, as well as accessible bacterial membrane components. ROS and structural oxygen vacancies cause oxidative stress and strong interaction sites, which are important in the antibacterial action of metal and metal oxide NPs when exposed to plant proteins [97]. Antimicrobial mechanism of edible films and coatings are shown in Table 1.

4.3. Moisture barrier

To reduce food waste and extend product shelf-life, high-quality

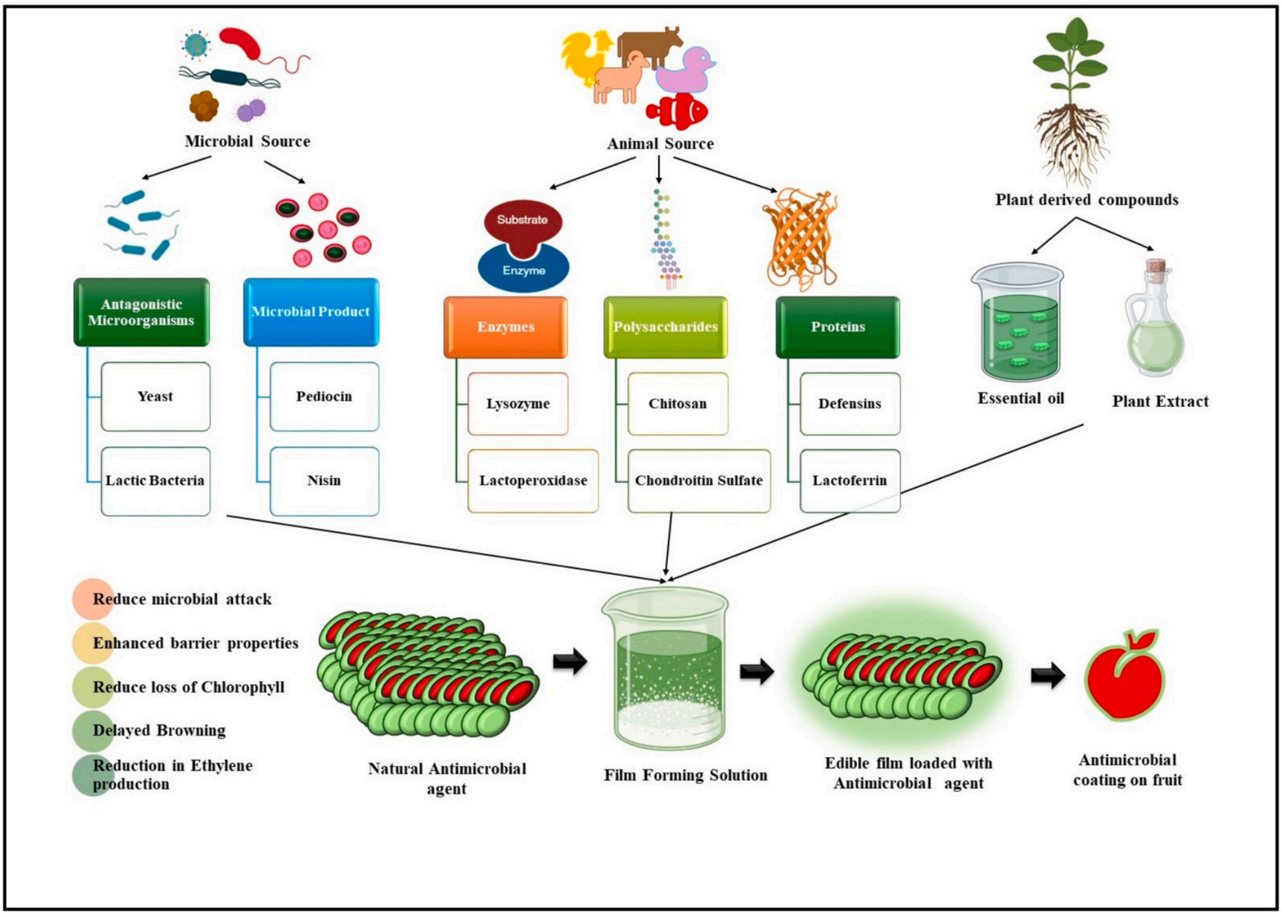

Fig. 3. Mechanism of antimicrobial action of edible films incorporated with nanoparticles.

Table 1
Antimicrobial mechanism of edible films and coating.

Category	Mode of action	References
Essential oils	Disrupts cell membrane, resulting in leakage of vital cell contents.	[98]
Organic Acids	Disturbs the pH of the cell, resulting in disturbance of enzyme activity and metabolic pathways	[99]
Enzymes	Disrupts bacterial cell wall and inhibits microbial growth	[100]
Metal-based nanoparticles	Metals disrupt protein functions and generates oxidative stress	[101]

packaging is used to prevent moisture from penetrating or entering. Glass and metal containers are widely used in the canning and alcoholic beverage packaging industries owing to their gas and water barrier properties. Nonetheless, they do not break down in landfills and require considerable energy expenditure for recycling as well as high transportation costs [102]. Polysaccharide-based materials absorb or release moisture until they reach equilibrium moisture content, which is determined by the temperature and humidity. Harvested fruits and vegetables continue to exhibit biological activity, resulting in the ongoing loss of water and solutes into the environment. This reduces post-harvest quality due to weight loss, shrivelling, and significantly shorter shelf life. The coatings provide a semi-permeable barrier that allows for the controlled exchange of moisture and gases, delaying overripening and senescence, while avoiding anaerobic conditions that might cause degradation. The barrier layer retains the interior gas composition and has properties comparable to those of modified atmospheric packing. They also prevent oxidative browning and premature maturation and modulate the respiratory rate [103]. A previous study found that polysaccharide-based edible films isolated from pumpkin, lentil, and quinoa seeds showed better water vapor permeability than polystyrene [104].

4.4. Prolong shelf-life

The use of edible coatings and films for food preservation, including vegetables, fruits, meat, and dry fruits, has a long history of use. Controlled entry and exit of moisture and gases is a mechanism that extends the shelf-life of fruits and vegetables beyond their usual shelf-life. Nonbiodegradable, non-sustainable packaging can be replaced with compostable, edible coatings, and films derived from natural biopolymers. The use of edible coatings and films has proven to be extremely beneficial in terms of prolonging the shelf-life of fruits and vegetables as well as being a sustainable and environmentally friendly approach to food packaging [105]. Consumer needs and lifestyles have significantly evolved in recent years. People now have less time to prepare food because of their work-life balance. Consequently, the demand for shelf-stable foods is expanding dramatically [106]. Edible film and coatings are also used to extend the shelf-life of a variety of items, including bakery and confectionery, meat and poultry, seafood, and dairy products. Researchers have found that applying *aloe vera*-based edible coverings to minimally processed kiwifruit slices increased their freshness when refrigerated [107]. Another study found that various

Edible coatings based on cassava starch, glycerol, carnauba wax, and stearic acid could be used to maintain the quality of apple slices. A Coatings formulation of 3 % (w/w) cassava starch, 1.5 % (w/w) glycerol, 0.2 % (w/w) carnauba wax, and 0.8 % (w/w) stearic acid showed better mechanical qualities and a barrier to moisture and gas exchange [108]. Various plant-based compounds that are useful for prolonging the shelf-life of food products are shown in Fig. 4.

4.5. Target nutrient supply

One of the primary benefits of utilizing edible coatings is the possibility of incorporating various active substances within the matrix of the Coatings, contributing not only to increasing the shelf-life but also to improving its organoleptic and nutritional properties. Edible coatings can prevent chemical, physical, and biological advances. The most common and difficult task in the fruit sector is to preserve and control freshness, avoid rotting, and reduce the proliferation of pathogenic microbes. This problem can be rectified by using an edible covering [109]. EC is a thin layer that works as a semipermeable membrane and barrier against gases and water leakage, slowing respiration, enzymatic browning, and the release of volatile compounds into the environment [110]. Many bioactive substances derived from food and phytochemicals have been developed and marketed as pharmaceutical formulations in the form of capsules, powders, gels, and solutions [111]. Studies have demonstrated the incorporation of nutraceutical ingredients into coatings or films, and studies are underway to determine the possible ingredient concentrations to be introduced into films or coatings that will not impact other film properties, such as barrier or mechanical properties. Therefore, they can be utilized as effective transporters of low-concentration nutrients in food products. The micro-and nano-encapsulation of these active chemicals can boost their stability for use in many food categories [112].

4.6. Physical and mechanical properties

Tensile tests were used to measure the tension force (MPa), elongation percentage at breaking (%), and elastic modulus (GPa). These values help predict package behaviour during handling and storage by providing information on flexibility, hardness, and elongation [113]. Novel bio-nanocomposite films and Edible coatings have been shown to improve product consistency, appearance, and longevity by forming semi-permeable barriers to gases and moisture such as carbon dioxide and oxygen [114]. The physical, chemical, and mechanical properties of biodegradable films with various compositions (gelatin-based, cornstarch, and carrageenan) were investigated. Films were produced using existing technologies, and the following characteristics were investigated: film thickness, mechanical properties, integral light transmission coefficient, degradation of these films in biological media, chemical resistance, and thermal properties [115]. The polymer architecture influences its mechanical properties. Edible coatings are a promising method for reducing packaging waste and extending the shelf-life of minimally processed fruit. Papaya puree (PP) was assessed as a foundation for edible films and coatings using alginate (0.5–1.0 g/100 mL), glycerol (0.8–1.5 g/100 mL), and citric acid (0.5–1.0 g/100 mL) [116]. A study discovered that combining *Artemisia sieberi* EO with CMC film resulted in good physical and mechanical qualities [117].

5. Technologies for fabrication of edible films and coatings

Edible films are wrapped around food products as a solid matrix, serving as the main packaging material without any sensory or nutritional benefits. This ingredient should be flavourless, colorless, and should not affect the sensory properties of the dish [118]. Edible film does not have a meaning similar to that of edible coatings. Edible film is a thin coating of edible ingredients used to cover a product or to separate

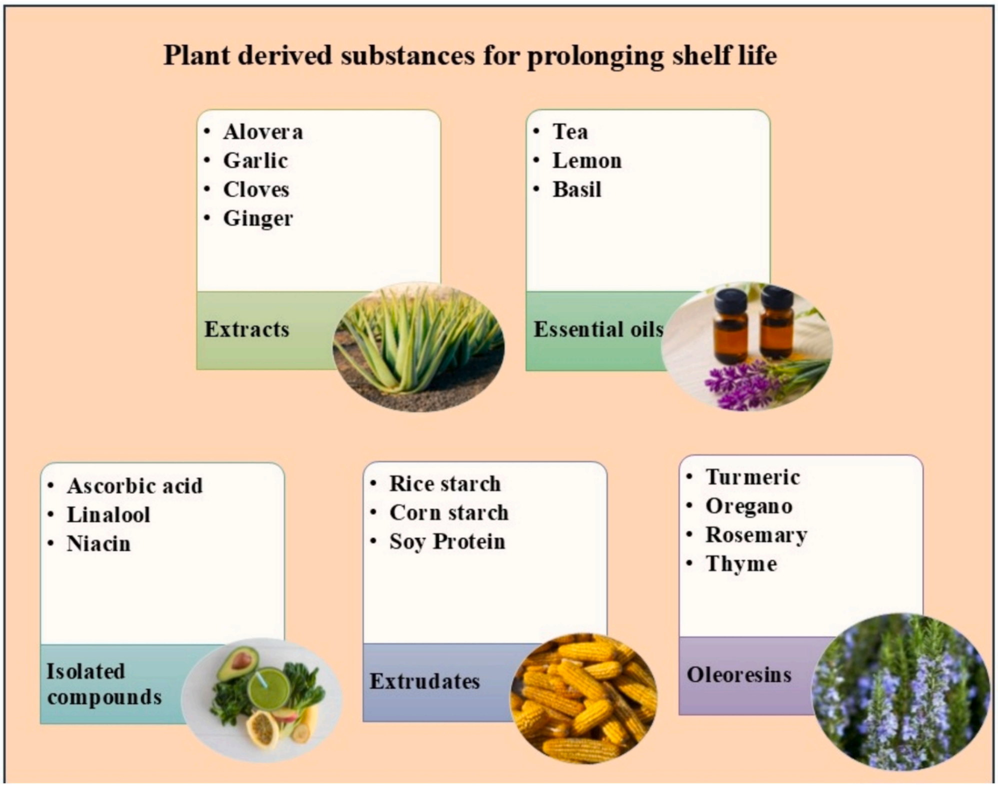

Fig. 4. Plant-based compounds that help in extending shelf-life.

its components. They act as barriers to mass transfer (of water vapor, gas, and solutes), thereby improving the handling of food and extending shelf-life. Their main benefit is that they may be eaten together with the dishes. Edible coatings are natural polymer-based packaging materials that are applied to products via immersion. They are also safe to consume along with the product. Edible coatings can carry food ingredients, including anti-browning, antibacterial, coloring, taste, nutritional, and seasoning agents [119]. Edible film-forming methods are classified as dry or wet (dry-casting) (wet-compression molding/extrusion), whereas edible coating forming methods include dipping, panning, spraying, fluidized bed processing, layer-by-layer deposition, and cross-linking.

5.1. Techniques involved in the formation of edible film

5.1.1. Solution casting

Solvent casting is a typical laboratory procedure that involves applying a polymeric solution over a surface and air-drying it in a vented oven to produce a film. After solvent evaporation, the film peeled from the surface and retained its physical shape. The biggest limitation of this technique is wrinkling and ripping during the peeling stage of the film. This variety can be regulated by selecting a suitable base frame material [120]. The process involved (1) solubilizing the biopolymer in a suitable solvent, (2) casting the solution in a mold, and (3) drying the cast solution (Fig. 5(A)). The formulation of edible film begins with the selection of a polymer or a polymer combination that creates the basic film. The chosen polymer was dissolved or dispersed in an appropriate solvent; for example, ethanol was used to dissolve the soy protein isolate polymers. This step is termed solubilization. Solvent casting relies on the polymer solubility to generate films. During the casting process, the resulting solution was poured into a predetermined mold or Teflon-coated glass plates. The drying process provided sufficient time for the solvent to evaporate, resulting in a polymer layer. Air driers, such as hot-air ovens, tray dryers, microwaves, and vacuum driers, are used for film casting to facilitate solvent removal and peeling. The air-drying technique for casting edible films is crucial for enhancing the intramolecular connection between polymer chains and generating a proper microstructure for the film [121]. The ultimate physical and chemical characteristics of a film depend on the casting solution composition, thickness, and drying conditions (temperature and relative humidity). Quick drying of the casting solution, translated by a high drying temperature, should be avoided to manage the intermolecular contacts in the film structure and the mobility of the polymeric chain, which may result in the production of a damaged film surface [122].

5.1.2. Extrusion

Extrusion is a widely used commercial technique to create polymeric films. The extrusion process involves three zones: feeding, kneading, and heating at the machine output [123]. Plasticizers, such as polyethylene glycol or sorbitol, are commonly added (10 % to 60 %). The tension, temperature, and density of the mixture increase when the components enter the kneading zone. This method for producing extruder-based edible films involves both mechanical (specific mechanical energy) and thermal (extruder barrel temperature) [124]. The extrusion screw speed affects the features of starch-based edible film, including the homogeneity, shear rate, and shear stress. It also controls the residence duration and allows for the insertion and removal of additives such as stabilizers. When the screw speed increased, the torque value of the starch-based film decreased [123].

Dry processing is commonly utilized in the production of thermoplastic packaging films containing starch and proteins such as maize starch, wheat bran, gluten protein, and soy protein. This process temperature profile enhances protein denaturation and aggregation as well as starch gelatinization and recrystallization [125]. This process produces films with diverse characteristics. The major steps of the extrusion process are outlined below:

(I). Mixing and hydration: Film-forming materials, plasticizers, cross-linking agents, and active chemicals are combined with water at a

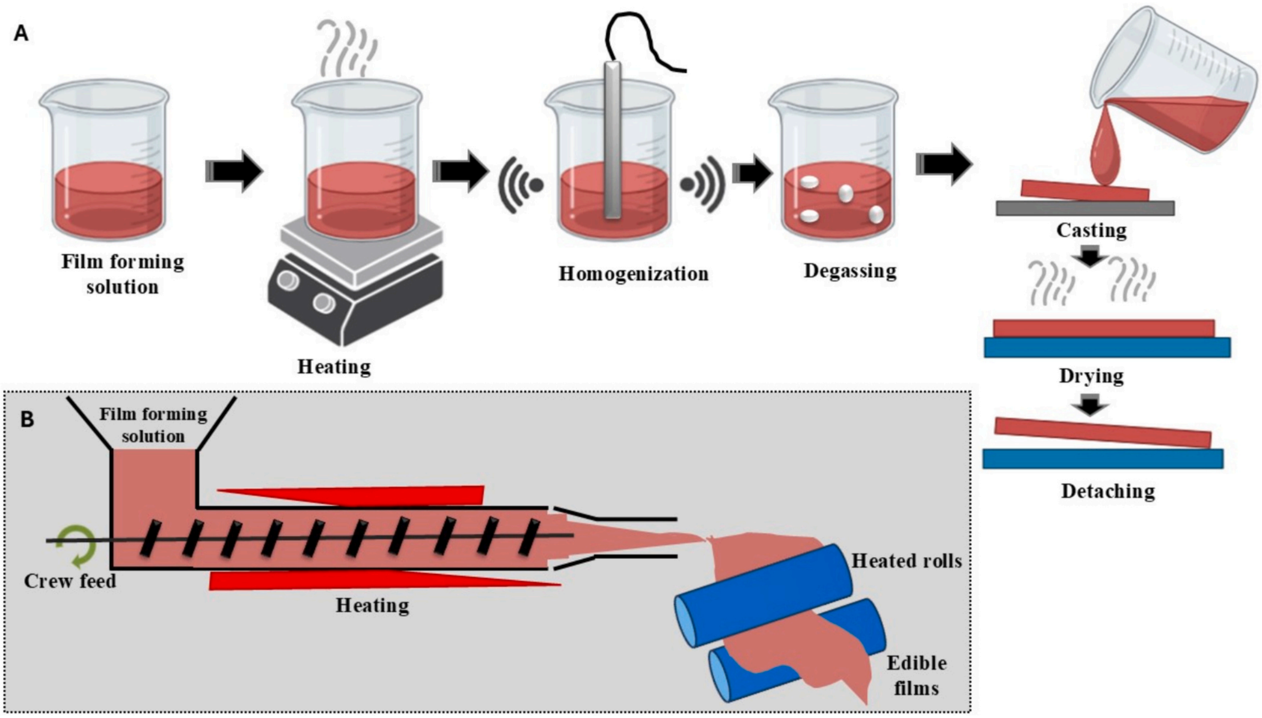

Fig. 5. Schematic diagram of (A) Solution casting, and (B) Extrusion.

certain temperature, causing them to hydrate and swell. Finally, the wet components were defoamed.

(II). Extrusion: The wet and dry components were fed into an extruder at a predetermined speed ratio. The screw warms and mixes various components under a high pressure before forcing them through a die to form a film. After extrusion, the resulting film was dried and chilled to form a finished edible film.

The technique of blow-molded films is similar to extrusion, except that the material is driven through a blow-molded machine to create an edible film [126]. The dry method provides benefits over the wet process in certain applications. For example, water-insoluble casein EF can be immediately produced by extrusion, thereby simplifying the production procedure. The thermoplastic technique alters the protein structure and functional characteristics of the film to a greater extent than wet casting [127]. Despite their potential benefits, there are few studies on the use of dry-processing technologies to create edible film with active chemicals. One probable explanation for these phenomena is that dry processing procedures often use very high temperatures, which might result in volatilization or destruction of thermally labile active chemicals. Researchers have attempted to address this problem [128]. A schematic of the extrusion method is shown in Fig. 5(B).

5.2. Techniques involved in the formation of edible coatings

5.2.1. Dipping

Dipping is the most popular laboratory-scale approach for coatings foods because of its ease of application, high coverage on uneven surfaces, and cost-effectiveness compared with other methods. This procedure involves submerging fruits or vegetables into a tank containing the coatings solution. The process parameters of the dipping technique include the solvent type, coatings solution temperature and viscosity, immersion and withdrawal speed, repetition, and immersion time. Despite its convenience, this approach has certain drawbacks, including the dilution of the coatings solution, residual buildup of coatings components, and the possibility of microbial development in the dipping tank [129]. To improve the retention, homogeneity, and adhesion of the coating's solution, vacuum impregnation is recommended for the coatings of fruits and vegetables. This procedure involved dipping the product into a coating's solution, withdrawing it, and draining the excess solution. As the pressure changes, the fluid in the food particles is swapped with the coating's liquid. Several parameters can affect coatings efficiency, including the duration of the vacuum period, vacuum pressure, and atmospheric restoration time. Despite its benefits, there is a paucity of research on the use of this technology to coat food ingredients [130]. Food items are often coated by dipping to avoid water loss and gas transfer, which requires placing a thin semipermeable membrane on the surface [131]. To remove the extra coatings from the food surfaces, the solution was drained. Finally, the fruit was dried to ensure durable coatings on the food surface on applying edible coatings to food products, perform these three steps: (1) immersion and dwelling, (2) deposition, and (3) evaporation of solvents. Atieno et al. (2019) tested several xanthan gum and guar gum mixtures to create edible coatings for cassava quality preservation [132]. The coatings were then subjected to dipping and spraying. Both application processes proved to be quite efficient, requiring only careful control of the coating's solution and the operating conditions. Finally, the best technique for coatings applications will be determined by other considerations, such as the ease of application. A schematic of the dipping method is shown in Fig. 6(A).

5.2.2. Panning

The panning technique involves coatings food and other materials in a large rotating basin, commonly referred to as a pan. The layering solution is then drizzled or dusted into a revolving dish to evenly distribute the coatings solution throughout the surface of the food item. This technique is widely used to achieve a uniform coatings and high-quality

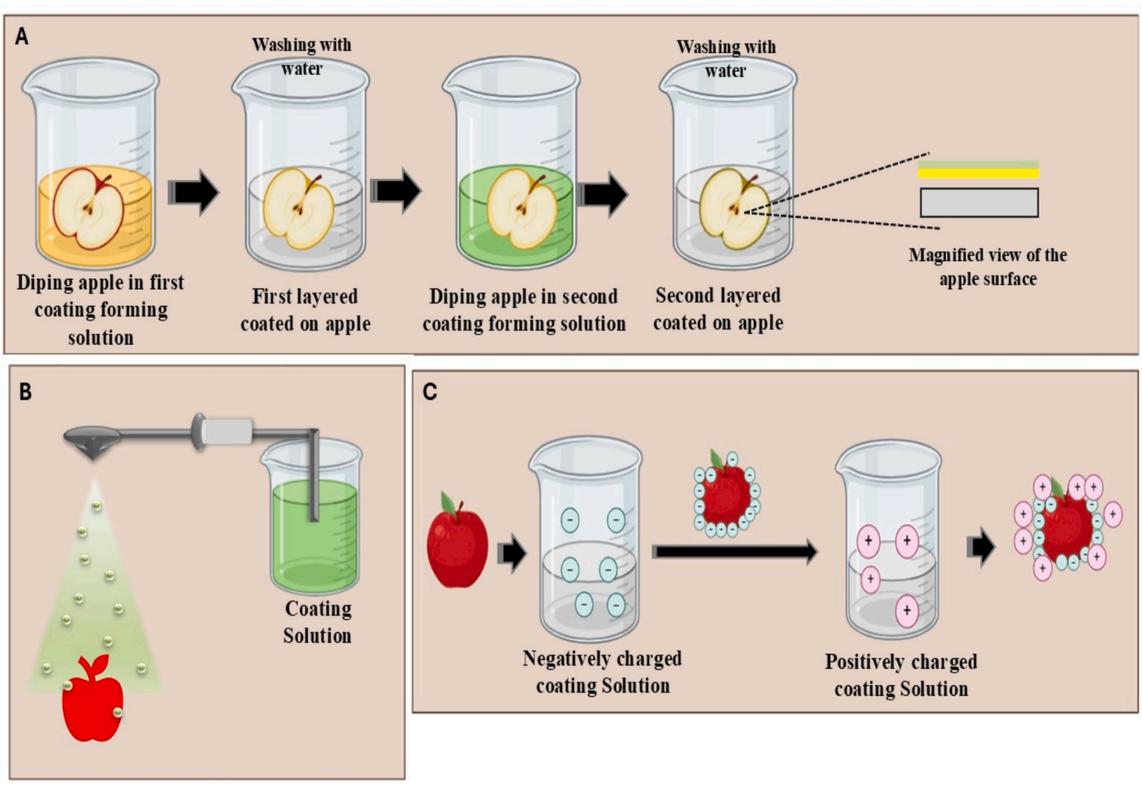

Fig. 6. Schematic representation of (A) Dipping, (B) Spraying and (C) Layer-by-layer deposition.

powder deposition. This is an effective way to apply the coatings material to conductive materials [133]. The panning method is employed in batch procedures to apply thin or thick coatings to hard almost spherical particles. The pharmaceutical, confectionary, and food-processing industries utilize this technology to coat items [134]. Pan coatings are a technique for covering a candy with a thin or thick layer that is applied successively, usually sugar syrup. Panning is the process of immersing food particles in sugar syrup and dusting them with sugar or other powder on their outermost layer. This method is more commonly employed for sweets such as jujubes. On the other hand, hard panning involves coatings food such as gumballs, peanuts, and chocolate candy with repeated layers of sugar syrup. After drying the initial layer, additional coats were applied to create a compact and dense surface [135]. A schematic of the panning process is shown in Fig. 6(B).

5.2.3. *Spraying*

The spraying approach creates a semi-permeable barrier over food by dispersing the coatings solution across the target surface via droplets. The coatings attributes depend on the polymeric solution parameters (density, viscosity, and surface tension), operating conditions (flow rate and air pressure), and system conditions (nozzle design and spray angle) [131]. This technique is cost-effective and efficient because of its minimal solvent usage, ability to apply multiple layers, avoidance of coatings solution contamination, temperature control, and ability to operate on large surfaces. Spraying enables the precise control of the coatings thickness, resulting in solutions as thin as 20 μm [122]. During air spray atomization, a low-speed liquid pours out a tube and is surrounded by a fast stream of air. Fluid-air friction plays an important role in promoting atomization; therefore, increasing fluid–air friction limits fluid flow and results in atomization. This low-cost spraying method uses air to spray droplets onto food goods [136]. Air-assisted airless atomization begins with air-assisted sprayers, which partly atomize the fluid with a specific nozzle tip. Atomization was completed using a small amount of compressed air from the air nozzle. This leads to the production of a highly atomized spray pattern. Air-assisted airless atomization eliminates numerous problems associated with the use of high-viscosity and high-solid coatings. Thus, this approach is a viable option for delivering high-quality finishes and large-scale production [134]. Pressure atomization involves the use of pressure to cover food. As an outcome, this method is commonly described as the "airless atomization technique." In this process, tiny nozzles are used to convey high-pressure energy, resulting in the surface tension and high viscosity of the coatings solution, which is then applied to food. To avoid destroying the film-forming machinery, the pressure was maintained at 3.5 bars throughout the operation [121]. A schematic of the spraying process is shown in Fig. 6 (C).

5.2.4. *Layer-by layer (LBL) deposition*

LBL processes have numerous applications in electrical, optical, biological, and membrane devices, including microcapsules, solar cells, biosensors, drug delivery systems, and separation membranes. LBL assembly is an adaptable technology that may generate charged thin-film active layers by absorbing oppositely charged polyelectrolytes or nanomaterials via multiple interactions, and has been shown to be an exciting technique for producing separation membranes with the desired characteristics. Nanocomposite membranes fabricated with several nanomaterials using the LBL method have recently gained popularity because of their superior membrane performance in terms of permeability, selectivity, antifouling, chlorine resistance, and long-term stability [137]. LBL has various benefits, including the capacity to contain and sustain the biological activity of therapeutic agents, cover multiple materials of all sizes (from nanoparticles to implants), and demonstrate tunable, targeted, and/or responsive drug-release behaviour [138].

Research has shown that the created LBL-edible coatings lowered water permeability but had no effect on gas permeability. Consequently, mango weight loss was greatly reduced owing to the restriction of water vapor escape. At the same time, LBL Coatings had no discernible influence on fruit respiration and did not induce anaerobic conditions. The covered fruit did not exhibit higher amounts of alcoholic fermentation or off-flavours [139]. The Edible coatings may efficiently manage moisture, gas, and organic volatile chemicals within fruits and their surroundings, as evidenced by several research [140]. LBL self-assembly is a method that uses polyelectrolytes to benefit from the electrical interactions between oppositely charged molecules. A previous study created EF using organic mucilage from *Opuntia ficus-indica* and pectin [141]. Another study demonstrated the use of plant pectin-based AM packaging sheets with sorbic acid for food applications. Functional packaging and coatings may considerably enhance the preservation of fruits and vegetables [142].

5.2.5. *Fluidized-bed*

The fluidized-bed coatings technique is commonly used in food processing to apply thin layers of Coatings materials to tiny, dry food particles. The coatings solution was sprayed onto the food surface using pressure nozzles to create a thin coatings layer. Fluidized Coatings involves spraying the coatings solution and suspension onto a fluidized food surface using numerous nozzles to create a shell-like structure [121]. This method is commonly used in food processing and research [143]. Fluidized bed technology, initially developed for the pharmaceutical sector, is now used to process food items, such as peanuts. Fluidized bed coatings allow for lower surfactant concentrations compared to dipping and panning, despite its higher cost. This method generally involves spraying a coatings solution or suspension onto the food surface using a series of nozzles on the surface of fluidized powders, thereby generating a shell structure. Fluidized beds are classified into three categories: top, bottom, and rotating. The top-spray design is commonly utilized in the food industry because of its superior performance. In this scenario, fluidization occurs when an upward fluid flow through a particle bed achieves a current velocity sufficient to prohibit particles from being carried with the flow. A fluidized bed produces particles larger than 100 μm because of the increased aggregation or unstable fluidization of smaller powder particles in traditional fluidized beds [144]. Polymers are often utilized as coatings materials, and the procedure is performed in a fluidized bed. The fluidized bed coatings use vertical airflow via a distributor plate at the bottom of the system to fluidize the particles. The coatings material, which might be a polymer journal solution or emulsion, was sprayed onto the fluidized particles using nozzles. The goal of this technique is to establish homogenous droplet deposition on a single particle, as well as over a complete particle population, which is required for a uniform coatings layer thickness [145].

6. Applications in smart food packaging industry

6.1. *Food preservation*

Food preservation technologies are currently confronting issues that increase the shelf-life of perishable foods. Applications of edible films and coatings made from food biopolymers have evolved dramatically in recent years. Edible packaging is composed of food-grade biopolymers, such as lipids, proteins, and polysaccharides derived from plants, animals, and marine life, as well as food processing by-products [146]. AM-edible coatings improve food safety and prevent spoilage. The inclusion of specific bioactive substances can significantly increase the antibacterial activity of edible film. AM substances can be introduced in either free or encapsulated forms. AMs are frequently encapsulated to increase their dispersion, compatibility, and stability inside the edible film. Furthermore, encapsulated AMs may display enhanced retention and release properties, such as extending AM activity throughout storage, by maintaining an antibacterial concentration above the minimum inhibitory concentration (MIC) at the food surface [147]. Edible coatings can withstand corrosion, browning, and nutritional loss with antioxidants. Edible film antioxidant and antibacterial active component investigations have many similarities. Film antioxidant properties depend on active ingredient, film-forming substance, encapsulation, and food type. Polyphenols, EOs, tocopherols, carotenoids, and plant extracts are antioxidant-rich foods. Singlet oxygen deactivation, peroxide enzyme inhibition, transition metal chelation, enzymatic detoxification of reactive oxygen species, and hydrogen radical transfer can all produce antioxidant action [148]. Packaging and preservation can increase the shelf-life of fruits and vegetables. Strong mechanical, barrier, thermal, and antibacterial qualities make antibacterial and packaging solutions effective. The phytochemical and physicochemical (respiration rate, weight loss, total soluble solids, pH) properties of newly picked and barely processed fruits and vegetables are preserved by edible film and coatings. Edible coatings and films have traditionally been flavourless and transparent to maintain food flavour [149].

6.2. Food packaging

Packaging helps preserve and promote food in the food industry. The quality of packaging material and its ability to preserve food from physicochemical and biological damage during manufacture and storage affects marketing. Primates protected their food from animal skins, broad leaves, and dried fruits like coconuts. Fabrics, glassware, and pottery have preserved meals. Recent research has focused on food preservation methods like cans, metal drums, flexible metals (aluminium, tin, and glass, as in bottles), solid and semi-solid plastics, and various types of elastomer paper, cardboard, and wood to extend storage and transport [150]. Proper packing may safeguard the collected items by lowering respiration, maturation, bacterial activity, ethylene production, and loss of moisture. Various active packaging methods can be used to reduce fruit and vegetable deterioration. Bio/polymeric nanocomposites have become increasingly popular in the food packaging industry [151]. Proper packing and coatings are essential for fresh fruits and vegetables as they tend to dry out rapidly and lose stiffness under typical circumstances. To reduce the dehydration rates, vegetables and fruits should be packaged with low water vapor permeability. Furthermore, oxygen permeability should be decreased to slow down respiration; however, it should not be too low to produce an anaerobic condition that is beneficial for off-flavour development and ethanol production, high mechanical and physical attributes that must demonstrate adequate resistance and strength throughout transportation and transport, and strong AM activity to reduce the development of microbes [152].

6.2.1. Fruits and vegetables

Edible coatings are environmentally friendly and can be safely consumed as part of the product, prolonging the shelf-life of fresh food. Consuming them prevents chronic diseases, strokes, cancers, osteoporosis, and neurological disorders [42]. Fruits and vegetables can lose their nutritional content because of unfavourable processing and storage conditions. During harvesting, shipping, and maintenance operations, approximately 30 % of the fruits and vegetables are affected by germs and insects that create tissue lesions and impair the integrity of the goods, eventually resulting in physiological alterations. To avoid deterioration, natural barriers can be strengthened or replaced with synthetic substances such as edible films and Coatings [153]. Polysaccharides are commonly used as matrix components in edible films and coatings for fruits and vegetables, according to several research. For example, two studies published in the past year focused on the development of active films and coatings to protect various types of fruits; in one of them, cassava starch films infused with clove essential oil were generated [154]. Another study reported that after being covered with nano-fibrillated cellulose packaging materials, the respiration rate of spinach significantly decreased during storage, resulting in extended shelf-life [155]. Robledo et al. (2018) diluted 10 % thymol nanoemulsions in water to create porous and heterogeneous quinoa-chitosan films [156]. Within seven days at 5 °C, it was shown that the coating effect on inoculated cherry tomatoes prevented fungal activity [157]. Apples were coated with a nanocomposite film made from 10 % soy protein isolate and 0.3 % sodium dodecyl sulfonate-modified nano-SiOx particles (coating time = 60 s). When this film was applied under ideal conditions with better physiological indices, the climacteric peak of apples was delayed to the fifth week. The increased water vapor permeability (WVP) was responsible for the weight loss of <12.80 % in the control fruits after 4 weeks. Yousuf and Srivastava (2019) investigated the use of honey and soy protein isolate coating for packaging fresh-cut pineapple [158]. The coating significantly increased the retention of phenolic components while extending the shelf-life of fresh-cut fruit for 16 days at 4 °C. Furthermore, the coating of linked soy protein isolate may inhibit the growth of microorganisms. Various edible films used for the packaging of fruits and vegetables, along with their effects, are shown in Table 2.

6.2.2. Bakery and confectionary products

Baked and extruded items, including cookies, snacks, and breakfast cereals, have a crispy feel owing to their low moisture content. An increase in moisture content causes loss of crispness during storage at higher relative humidity levels. Bakeries use edible coatings and films to reduce water vapor permeability, exchange oxygen, prevent fat and oil dripping, protect from light, provide physical and mechanical protection, and extend shelf-life. These edible films and coatings can be used in a variety of bakery items [168]. Edible films and coatings of similar qualities can be used as bakery products. Probiotic inclusion in edible films or coatings has garnered enormous appeal among researchers as a viable subject for investigation. Multiple studies have been conducted to investigate the impact of probiotic edible films and coatings on the shelf-life and quality of bakery items. Research has shown that using a triticale-based edible film layer on muffins can help prevent staling. Weight, height, volume, density, color, texture, and image analyses were used to compare the control and coated muffins during storage. Triticale-coated muffins had lower hardness values and stalled faster than the control muffins [168].

6.2.3. Meat and poultry-based products

Bacteria can readily grow in meat due to its sensitive tissue structure. Edible films/coatings can reduce infectious microorganisms and improve the shelf-life of meat products [168]. Meat texture is influenced by both the protein composition and water concentration. It is important to prevent water loss while preserving beef. Edible coatings can prevent spoilage and pathogenic microorganisms on meat surfaces, reduce moisture loss during storage, preserve juices, and limit volatile taste loss and foreign odours when packed in plastic retail trays [8]. Meat tissue structure and various processing methods can promote germ growth. AM and intelligent packaging have emerged as barriers to food safety in recent years. Owing to the vast and varied variety of meat and poultry products produced, several strategies for managing food-borne diseases and extending product shelf-life are required [169]. AM-treated edible films and coatings can reduce pathogenic germs and increase the shelf-life of foods. Applying a coatings or films to meat products may minimize moisture loss, preserve juices, reduce rancidity, and prevent volatile flavour loss and foreign odours [170]. A research found that applying the *Mediterranean* plant garlic with alginate to lamb reduces lightness, redness, lipid oxidation, and water loss but increases yellowness and has no effect on pH [171]. Another study reported that the antibacterial efficacy of an edible film made of ovo-transferrin and κ-carrageenan on fresh chicken breast was efficient against *Salmonella typhimurium*, *Staphylococcus aureus*, *Candida albicans*, and *E. coli* [172]. Xin et al. (2020) created a zein/potato starch-based film containing chitosan nanoparticles to preserve Schizothorax prenati fillets [173]. The authors discovered that the devised packaging slowed physicochemical changes in the fillets, increasing their shelf life by 15 days.

Table 2
Edible films incorporated with active compounds used for packaging of fruits and vegetables.

Film or coatings matrix	Active compounds/ nanoparticles incorporated	Food items	Benefits/advantages	References
Carnauba wax	Nano-clay	Orange fruit	Enhancement of orange sensory acceptability, nutritional quality, lower orange weight loss and respiration rate	[3]
Cassava starch	Nano-Zno	Fresh sliced okra	Better product quality	[159]
Carboxymethyl cellulose (CMC)- Guar gum	Silver Nps	Strawberry	Inhibits functionality of bacteria and fungi. Lower weight loss	[160]
Soy protein isolate	Zno NP	Banana	Slow down ripening and weight loss. Inhibits physiochemical changes	[161]
Polylactic acid	Nano-Ag and Nano-TiO_2	Mango	Inhibits microbial growth. Prevents physiochemical changes.	[162]
Carboxymethyl cellulose	Nano-Zno	Pomegranate	Reduced weight loss, inhibits molds and yeast, higher antioxidant property.	[163]
Polylactic acid	Zno	Cut apple	Better physiochemical and sensory property	[164]
Carrageenan	Nano-Zno	Mango	Inhibits development of *E. coli*. Extends shelf-life	[165]
Cellulose nanofibrils	Ag-NPs	Fruits and vegetables	Inhibits various bacterial growth	[166]
Sodium alginate	Nano-Zno	Strawberry	Extends the storage life, inhibits bacterial growth	[167]

6.2.4. *Fish-based products*

Fish products often deteriorate through lipid oxidation, enzymatic reactions, protein breakdown, metabolic activities, and microbial activity. Cross-contaminated microorganisms can swiftly multiply and shorten the shelf-life of a product. Furthermore, the high concentration of polyunsaturated lipids in fish makes them more susceptible to oxidation [174]. The primary purpose of utilizing edible films and coatings in seafood is to avoid contamination by rotting organisms. In numerous instances, the intended inhibitor *is* L. *monocytogenes* growth, which poses the greatest danger to freshly processed cold-smoked salmon. Another significant purpose is to minimize oxidative spoiling in the case of fat specimens by using antioxidant compounds, as well as to prevent moisture loss [175]. Lipid oxidation causes discoloration, odd-taste, and formation of potentially hazardous chemicals in seafood. Edible films and coatings act as oxygen barriers, reducing lipid oxidation in frozen items during storage. Furthermore, plant extracts can help sustain the activity of antioxidant enzymes, such as dismutase peroxide and glutathione peroxide, in the food matrix. Edible films and coatings suppress oxidation, reducing yellowing and lightness [176]. A study reported that alginate coatings incorporated with clove EO helps in the storage of silver carp fillets, which maintains their chemical properties and inhibits microbial growth [177]. Another study demonstrated that tartary buckwheat (*Fagopyrum tataricum Gaertn*) incorporated with 1 % nisin helps in the storage of tilapia fillets (*Oreochromis niloticus*) by retarding nucleotide breakdown, lipid oxidation, and protein degradation [178]. The various edible films used for the packaging of fish and fish products are shown in Table 3. When edible films/coatings applied to *Otolithes ruber* fish (16 days at 4 °C), a polylactic acid film containing zinc oxide (1.5 %), *Menthe piperita L.* EOs (at 0.5, 1 and 1.5 %), and *Zataria multiflora Boiss* EO enhanced the film's phenolic content, AO potential, and AM activity. This contributed to the shelf life being extended from 8 to 16 days [179]. During the storage period, the sensory characteristics of trout fillets coated with chitosan and lactoperoxidase system were better retained than those that were untreated or just coated with chitosan [180]. Researchers determined, the impact of 50 and 100 mg/kg of 6-gingerol on lipid oxidation in red drum fillets while they are refrigerated. The concentration-dependent rise in 6-gingerol's AO activity suggests that it can be used to prevent lipid oxidation in the food chain by hydrogen transfer [181].

6.2.5. *Dairy-based products*

Dairy products provide essential nutrients for both children and adults. Dairy products are milk-derived compounds that may contain food additives and other processing elements. The consumption of dairy products is increasing, particularly in emerging nations, because of population expansion and dietary changes [185]. Cheese is a food product that uses edible films and coatings to minimize the loss [186]. Cheese is an intricate meal composed of casein, fat, and water. Microbial stability must be regulated in both fresh and semi-hard cheeses. Edible films and coatings can restrict microbial growth and reduce post-processing contamination with L. *monocytogenes*. To maintain cheese quality, the coatings or film must also allow gas exchange with the surrounding environment [187]. A study by Guitián et al. (2019) aimed to protect cheese. In this study, antimicrobial agar edible coatings were blended with a bacteriocin (*L. monocytogenes enterocin*), which is a successful, low-cost, natural, and secure option to inhibit the growth of foodborne pathogens [186]. Table 4 lists a few plant-based edible coatings for dairy products.

7. Regulatory challenges and opportunities

Despite tremendous development has been achieved in the creation of plant-based materials and edible films, issues such as ecological responsibility, regulation, sustainability, and functionality optimization still exist. By tackling these problems and furthering research in the field, plant-based products and edible films have the possibility to

Table 3
Edible films used for the packaging of fish-based products.

Film or coatings matrix	Active compounds/nanoparticles incorporated	Food items	Benefits/advantages	References
Alginate	6-Gingerol	Sea bream (*Pagrosomus major*) fillets	Extends its shelf-life	[181]
Alginate	Clove essential oil	Silver carp	Maintains the chemical properties and inhibits microbial growth	[177]
Alginate-ε-polylysine		Japanese sea bass	Maintains the sensory quality by retarding nucleotide breakdown, lipid oxidation and protein degradation	[182]
Tartary buckwheat (*Fagopyrum tataricum Gaertn.*)	1 % Nisin	Tilapia (*Oreochromis niloticus*) fillets	Inhibits bacterial growth, and retards lipid oxidation	[178]
Carrageenan		Rainbow trout fillets	Inhibits bacterial growth, and retards lipid oxidation	[183]
Carboxy methyl cellulose	*Zataria multiflora Boiss.* essential oil and grape seed extract	Rainbow trout fillets	Increased shelf-life	[184]

Table 4
Edible plant-based coating for dairy products.

Food product	Additives	Plant-based edible materials	Effects on the product	References
Cheese mozzarella is kept at 7 °C.	Natamycin	Carboxymethyl cellulose (CMC)	It inhibits *Aspergillus flavus*, *A. fumigatus*, *A. niger*, *Candida albicans*, *Penicillium citrinum*, yeast, and mold and doubles the shelf-life.	[188]
Ultrafiltrated (UF) soft cheese	Sodium alginate and chitosan	CMC	Increases the shelf-life by 45 days and exhibits strong antibacterial activity.	[189]
Mozzarella cheese	Glycerol and starch	Pectin extracted from banana peel	Extends the shelf-life for up to 21 days and exhibits antibacterial action against *Staphylococcus aureus*.	[190]
Eastern European curd cheese	Whey protein concentrates and glycerol	Cinnamon bark CO_2 extract	By maintaining moisture, preventing the growth of yeasts and molds, and prolonging the shelf life of both packaged and package-free cheese, coating influences its appearance and color.	[191]
Iranian white cheese	Glycerol and whey protein concentrate	Cumin essential oil	Prolongs the shelf-life from 10 to 28 days, keeps the moisture content constant, and lowers the levels of *Listeria monocytogenes*, *S. aureus*, *E. coli*, yeast, and mold.	[192]

transform the packaging sector and contribute to an environmentally conscious and ecologically friendly destiny [193]. One of the most significant issues in the field of plant-based products and edible films is guaranteeing sustainability across the whole lifecycle, from raw material sourcing to disposal. The availability and scalability of plant-based resources must be carefully considered in order to meet the expanding need for environmentally friendly packaging materials. Furthermore, the creation of efficient and ecologically conscious processing procedures is critical for reducing energy consumption and impacts on the environment [194]. Protein films' barrier characteristics are determined by their polarity. Polar molecules, such as water vapor, have great permeability through protein sheets. Protein-derived materials, on the other hand, have minimal permeability to oxygen and oils, both of which are nonpolar. Protein films have low moisture and water vapor resistance capability due to their hydrophilic properties but have high oxygen barrier characteristics. This is one of the most significant barriers to the use of protein films in food packaging, and it is the primary reason why this type of packaging cannot be expected to have comparable barrier qualities to synthetic polymers. Some of the limitations of these plant-based films are mechanical weakness, poor water resistance, scalability issues, or cost-effectiveness. The most essential criteria for water vapor permeability studies are relative humidity and temperature. The larger the difference in water humidity, the more water vapor can pass through a polymeric film. Biopolymer films have higher water vapor permeability than synthetic films, likely due to their origin and production characteristics. The majority of hydrocolloid films are hydrophilic materials, and scientists have been particularly interested in improving their water resistance in recent decades. Furthermore, water resistance is dependent on film thickness, which influences other physical properties of films.

8. Consumer acceptance

The acceptance of edible films and coatings by consumers is a pivotal factor influencing their widespread adoption in the food industry. These edible packaging materials are often appreciated for their potential to enhance food safety and shelf life while reducing reliance on plastic packaging. However, their success largely depends on how well they meet consumer expectations in terms of sensory characteristics, such as taste, aroma, texture, and visual appearance [195]. Transparent labelling and effective communication about the benefits, safety, and functionality of these materials are essential to foster trust and acceptance. Applications that are already familiar, such as coatings on fruits, confections, or meat products, tend to receive more positive responses, indicating that gradual market introduction through such products may be a successful strategy. The regulatory framework for plant-based products and edible films is changing, so there is a requirement for clear regulations and norms. Substances for food contact must meet safety standards and comply with applicable laws [196]. Furthermore, consumer acceptance and impression are critical factors in the broad acceptance of plant-based packaging. Educating customers on the perks and environmentally friendly qualities of these materials can help increase their acceptance and commercial penetration. Therefore, consumer acceptance of edible films is shaped by a complex interplay of sensory, health, cultural, economic, and environmental factors, requiring a well-informed and multidisciplinary approach for successful implementation.

9. Environmental impacts and biodegradability

The worldwide packaging materials market was $348.08 billion in 2020, and it is expected to grow by 33.6 % to $465 billion in 2028. Plastic packaging appears to be more cost-effective than biodegradable alternatives. The increasing demand for sustainable alternatives to petroleum-based plastics has led to a significant focus on biodegradable films and coatings. These materials, often derived from renewable sources such as starch, cellulose, polylactic acid (PLA), and polyhydroxyalkanoates (PHA), are gaining attention for their reduced carbon footprint. One of the most widely used tools to evaluate their environmental sustainability is life cycle assessment (LCA), which examines the environmental impacts of a product throughout its life span [197]. Although petroleum is the primary element in these polymers, increased consumption ultimately results in socioeconomic challenges such as scarcity and escalating oil costs worldwide, as well as environmental concerns. To address these issues, producers must invest in biodegradable polymers, such as plant proteins. Adopting a circular economy model will help retain more assets in both the production and consumption circuits, resulting in a smaller amount of waste [198]. Biodegradable polymers have been expanded to address the environmental concerns raised by traditional plastics. Increased awareness of the harmful consequences of petroleum-based plastics has been the primary driver of the bioplastic packaging sector [199]. In 2020, global bioplastic production was estimated to be 2.11 million tonnes (MTs), with the packaging industry accounting for 47 % of this total, making it the largest market segment in the bioplastics industry. The global production of bioplastics is expected to reach 2.87 MTs by 2025 [200].

10. Conclusions and future perspectives

The packaging sector could undergo a revolution, and environmentally friendly procedures could be promoted through the development of plant-based materials and edible films. Utilizing renewable resources lowers carbon emissions and dependency on fossil fuels. Edible films and plant-based materials have the potential to drastically change the packaging sector by offering environmentally friendly substitutes for traditional materials. These materials can help create a future that is more sustainable and kinder to the environment, with continued study, developments in technology, and improved consumer awareness. Adopting these ideas can help minimize plastic waste, migrate to a circular economy, and improve the earth's sustainability and health for future generations. Study and development focus on customer acceptability, legislation, scalability, and sustainability. Processing innovations like 3D printing and nanotechnology offer exciting prospects for personalizing materials and packaging. Also, adding active and intelligent components to plant-based materials can improve food quality, safety, and preservation. Collaboration between academics, companies, and regulators is essential for innovation and knowledge exchange in the field. If everyone collaborates to create consistent guidelines and procedures, it will be simpler to ensure that plant-based materials and edible films are safe and adhere to food packaging regulations. Investigating advanced processing techniques like electrospinning, nanotechnology, and bio-fabrication can improve and increase the utility of plant-based products.

CRediT authorship contribution statement

Ammar B. Altemimi: Methodology. **Pinku Chandra Nath:** Conceptualization, Writing – review & editing. **Vinay Kumar Pandey:** Investigation, Writing – review & editing. **Pooja Yadav:** Visualization. **Anjali Tripathi:** Resources. **Sarvesh Rustagi:** Data curation. **Ruby Prakash:** Writing – original draft.

Consent to participate

Consent forms were obtained from all the subjects after the procedure was explained to them.

Consent for publication

All authors have given their consent for publication.

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Data availability

No data has been used in the conduction of this study.

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